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Electrostatic force microscopy study of the electric field distribution in semiconductor laser diodes under applied biases

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In the semiconductor laser diodes the inner electric field distribution is the characteristic of significant interest in device design and failure analysis. In the modern lasers the applied voltage usually drops within the narrow layers of submicron range, and the precise information on the electric field distribution must be extracted by means of methods having nanometer spatial resolution. The electrostatic force microscopy (EFM [1] is the excellent candidate to solve this problem. This technique presents the development of the atomic force microscopy (AFM [2] which allows direct measuring of the electrostatic force acting between the nanometer-size probe and the surface. The electrostatic force in such system depends on the capacitance and the potential difference between the probe and the surface. These two contributions into the force can be separated in EFM, thus providing a way for high resolution surface potential and capacitance mapping. Until now only a few EFM studies were performed to probe electric characteristics of semiconductor light emitting devices [3–5]. The potential profiles in the devices under applied bias were measured for AlGaSb/GaSb based lasers [4] and for GaP based light emitting diodes [3]. Robin *et.al.* [5] investigated the potential and the corresponding electric field profiles in InP/InGaAsP p-i-n laser diode without external bias.

In this work we applied the EFM method to investigate AlGaAs/GaAs and InGaP/GaAs based p-i-n laser diodes and have found the main features of the electric field and capacitance distributions on the cross-sections of the devices under the applied forward and backward biases. The fine structure of the electric field distribution presented by two spikes localized at the n-emitter/i-waveguide and p-emitter/i-waveguide interfaces is analyzed. Our study shows that at the low level of the injection current the inner electric field induced by the applied bias is concentrated in the vicinity of the n-emitter/i-waveguide interface, while at the high level of injection it is redistributed in favor of the p-emitter/i-waveguide interface. With increasing forward bias the growth and broadening of the capacitance signal at the undoped waveguide region is also observed, that may reflect the injected carriers distribution.

We have used the EFM method in which an alternative bias at the frequency ω is applied to the AFM probe inducing its mechanical oscillations due to electrostatic force variations. The first and the second harmonics ($H(\omega)$, $H(2\omega)$) of oscillations, which are two main EFM signals, can be detected by lock-in technique. $H(\omega)$ depends mainly on the probe-surface potential difference, $H(2\omega)$ is proportional to the corresponding capacitance. The AFM operates in tapping mode and in addition to the EFM signals the topography data are measured.

The microscope used for the measurements is an air-AFM system (Autoprobe CP Research, ThermoMicroscopes). Alternative voltage is applied to the highly doped Si probe

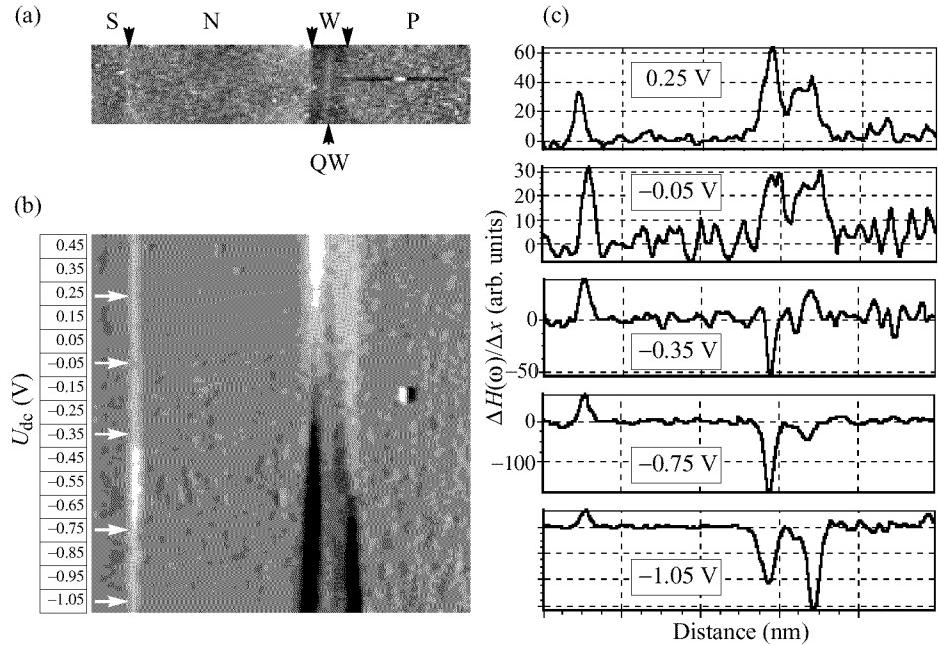


Fig. 1.

at a typical frequency of around 50 KHz and a voltage amplitude of 0.7 V. The EFM signals are analyzed through a Stanford Lock-in Amplifier 8230. The studied lasers are biased by the constant voltage source built in the microscope.

Figure 1(a) shows an AFM tapping mode topography image of the cleaved surface of one of the p-i-n laser diodes studied in this work. The structure was grown by the molecular beam epitaxy and consists of an n-doped GaAs substrate (S), an n-doped (Si) 2 μ m-thick AlGaAs emitter (N), an undoped 0.4 μ m-thick GaAs waveguide (W) centered with 9 nm InGaAs quantum well (QW), a p-doped (Be) 2 μ m-thick AlGaAs emitter (P) followed by heavily doped p-GaAs contact layer. All the main layers of the structure can be identified in the image, in which the darker contrast corresponds to the depression of the surface relief. The waveguide region of the structure is several angstroms lower than n- and p-emitters due to known difference in oxide layer thickness on GaAs and AlGaAs [6]. The bright line in the middle of the waveguide corresponds to the compressed InGaAs QW. As it was shown earlier, thin compressed layers can noticeably extrude out on the cleavage [7].

In Figure 1(b) the variations of the $\delta H(\omega)/\delta x$ magnitude over the studied surface area are presented. The data were obtained as follows. First, simultaneously with the topography data acquisition, the $H(\omega)$ signal was measured as a function of the dc bias applied to the N-contact of the laser; the bias is decreased by the steps of 0.1 V every 1/16-th of the image height from 0.45 V (top of image) to -1.05 V (bottom of image). Then, the first derivative $\delta H(\omega)/\delta x$ was calculated numerically along the direction x perpendicular to the interfaces. Figure 1(c) shows the profiles of $\delta H(\omega)/\delta x$ taken under different applied bias (the white arrows in Fig. 1(b) indicate the lines in image along which the profiles are taken). The meaning of the $\delta H(\omega)/\delta x$ signal is the electric field at the surface in the direction perpendicular to the interfaces. Variations of this field should reflect variations

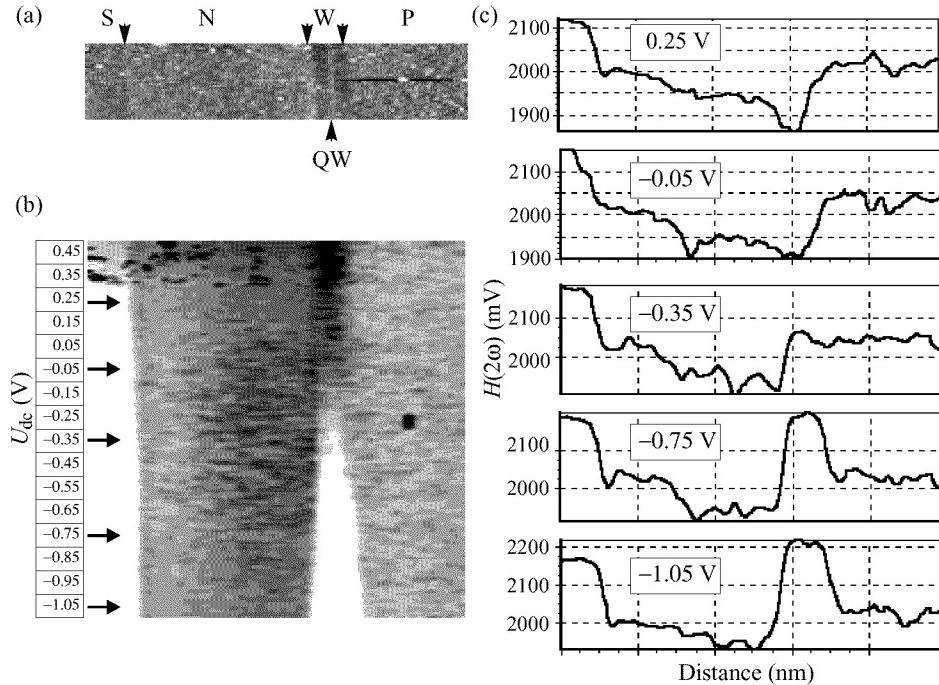


Fig. 2.

of the inner electrical field in laser diodes in the same direction. Without bias (a profile taken at -0.05 V) the distribution of the electric field is symmetric and formed by the two spikes whose extrema are localized near the waveguide interfaces. For the low level of injection current, the inner electric field is concentrated at the n-emitter/i-waveguide interface (the left spike in the profiles taken at 0.25 V, -0.35 V and -0.75 V is mainly changed). However, under the high level of injection, the redistribution of the inner electric field in favor of the p-emitter/i-waveguide interface is observed (the right spike in the profile taken at -1.05 V is deeper than the left one). It is interesting to note considerable reduction of the electric field at the waveguide center.

The variations of the $H(2\omega)$ signal (capacitance) are shown in Fig. 2(b) (the applied bias is changed in the same manner as in Fig. 1(b)) and in Fig. 2(c) with the profiles of $H(2\omega)$ along the lines marked by the black arrows in Fig. 2(b). The white band in the left part of the image in Fig. 2(b) is attributed to the n-GaAs substrate, see also the topography image in Fig. 2(a). An increase of the capacitance at the n-GaAs substrate compared to the n- and p-AlGaAs emitters is related to the thinner native oxide on GaAs [6]. The capacitance at the substrate and the emitter layers does not depend on the applied bias. However, the applied bias affects strongly the capacitance at the waveguide region. For the backward biases, the signal has low magnitude. Under the forward bias of approximately -0.35 V, there appear at the middle of the waveguide the spike in the $H(2\omega)$ signal which amplitude is higher than the signal level at the surrounding emitters. The spike grows in height and broadens with increasing forward bias, and at -1.05 V (see Fig. 2(c)) its top is formed by the wide ~ 0.4 μ m plateau that coincides well with the position of the waveguide.

In conclusion, we present a new and direct electrostatic force microscopy method to resolve the electric field and capacitance distributions in laser diodes. Using this method we have investigated the fine structure of the electric field in AlGaAs/GaAs and InGaP/GaAs p-i-n based laser diodes under forward and backward biases. We have also found a strong increase in the capacitance at the waveguide under forward biases. We believe that this effect is related to the carriers injection into the waveguide and can be used to study the injected carriers distribution.

The presented method can be also used to study the electric fields in the other semiconductor devices.

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